



The Rise and Fall of the Ridge

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Abstract

Recent data from heavy ion collisions at RHIC show unexpectedly large near-angle correlations that broaden longitudinally with centrality. The amplitude of this ridge-like correlation rises rapidly with centrality, reaches a maximum, and then falls in the most central collisions. In this talk we explain how this behavior can be easily understood in a picture where final momentum-space correlations are driven by initial coordinate space density fluctuations. We propose $v_n^2/\varepsilon_{n,part}^2$ as a useful way to study these effects and explain what it tells us about the collision dynamics.

Keywords:

Introduction: The motivation for the construction of the Relativistic Heavy Ion Collider at Brookhaven National Laboratory was to collide heavy nuclei in order to form a state of matter called the Quark Gluon Plasma (QGP) [1]. These collisions deposit many TeV into a region the size of a nucleus. The matter left behind in that region is so hot and dense that hadronic matter undergoes a phase transition into a form of matter where quarks and gluons are the relevant degrees of freedom, not hadrons [2]. This is the state of matter that existed when the universe was less than a microsecond old and still very hot.

Correlations and fluctuations are an invaluable tool for probing the dynamics of heavy-ion collisions. Data from the experiments at RHIC reveal interesting features in the two-particle correlation landscape [3, 4]. Specifically, it has been found that correlation structures exist that are unique to Nucleus-Nucleus collisions. While two-particle correlations in p+p and d+Au collisions show a peak narrow in azimuth and rapidity, the near-side peak in Au+Au collisions broadens substantially in the longitudinal direction and narrows in azimuth. An analysis of the width of the peak for particles of all p_T finds the correlation extends across nearly 2 units of pseudo-rapidity ($\Delta\eta = 2$) [4]. When triggering on higher momentum particles ($p_T > 2$ GeV/c for example), the correlation extends beyond the acceptance of the STAR detector ($\Delta\eta < 2$) and perhaps as far as $\Delta\eta = 4$ as indicated by PHOBOS data [4].

STAR has found that the amplitude of this correlation shows a rather rapid rise with collision centrality [3] before reaching a maximum and falling off in the most central bins. This drop in the most central bins shows up for both $\sqrt{s_{NN}} = 200$ and 62.4 GeV but is often overlooked. In this talk we present a geometric explanation for the centrality dependence of the ridge amplitude. We'll use the centrality dependence of v_2/ε_2 , dN/dy , and the third harmonic participant eccentricity $\varepsilon_{3,part}^2$ [5] to predict the amplitude of the near-side ridge correlation (A_1). Given the apparent relevance of initial-state density fluctuations to the final, momentum-space correlations, we advocate the transfer function $v_n^2/\varepsilon_{n,part}^2$ as a valuable observable for studying the length scales in heavy-ion collisions. We extract the transfer functions from intermediate p_T di-hadron correlation data where evidence has been presented for conical emission [6].

Three Premises: It has been shown by the STAR collaboration that the second harmonic component of the near-side ridge in the two particle correlations can account for nearly all of the difference between the two and four particle cumulant v_2 [7]. It was argued that v_2 fluctuations must therefore be tiny: many times smaller than the fluctuations

predicted from eccentricity models [8]. In that case, a major revision of our understanding of heavy-ion collisions would be required. We've argued previously, however, that eccentricity fluctuations can give rise to v_n fluctuations for more harmonics than just $n = 2$, and that those fluctuations could therefore be the source of the near-side ridge [9] (especially if the v_n fluctuations depend on pseudo-rapidity difference $\Delta\eta$ i.e. $\langle v_n(\eta)v_n(\eta + \Delta\eta) \rangle \equiv f(\Delta\eta)$). This idea has been born out by calculations from several groups [10, 5, 11, 12]. To test this conjecture, we will attempt to explain the centrality dependence of the near-side ridge amplitude A_1 from eccentricity fluctuations. we start with three simple premises:

- the expansion of the fireball created in heavy-ion collisions converts anisotropies from coordinate-space into momentum-space,
- the conversion efficiency increases with density,
- and the relevant expansion plane is the participant plane.

The participant plane can be defined for any harmonic number and a system with a lumpy initial energy density will give rise to finite participant eccentricity at several harmonics [5, 13]. This becomes conceptually clear when eccentricity is recast in terms of a harmonic decomposition of the azimuthal dependence of the initial density. Our calculation of the centrality dependence of A_1 will depend on the higher harmonic terms in an eccentricity model.

Higher Harmonics, Even the Odd: Fig. 1 (left) shows the n^{th} -harmonic participant eccentricity $\langle \epsilon_{n,\text{part}}^2 \rangle$ as defined in Ref. [5] for central Au+Au collisions from a Monte-Carlo Glauber model. Typically the participant eccentricity is calculated based on the positions of point-like participants (that is the participant is said to exist at a precise x and y position). Those results are labeled $r_{\text{part}} = 0.0$ fm. One can also calculate the eccentricity from a more physically realistic model with participants smeared over some region. This is done by treating each participant as many points distributed within a disk of some finite radius r_{part} . Increasing r_{part} washes out the higher $\langle \epsilon_{n,\text{part}}^2 \rangle$ terms. The right panel of Fig. 1 shows the ratio of $\langle \epsilon_{n,\text{part}}^2 \rangle$ for a given r_{part} value divided by $\langle \epsilon_{n,\text{part}}^2 \rangle$ for $r_{\text{part}} = 0$. The curves are labeled l_{mfp} instead of r_{part} and the ratio $l_{\text{mfp}}/\text{ideal}$ for reasons explained below.

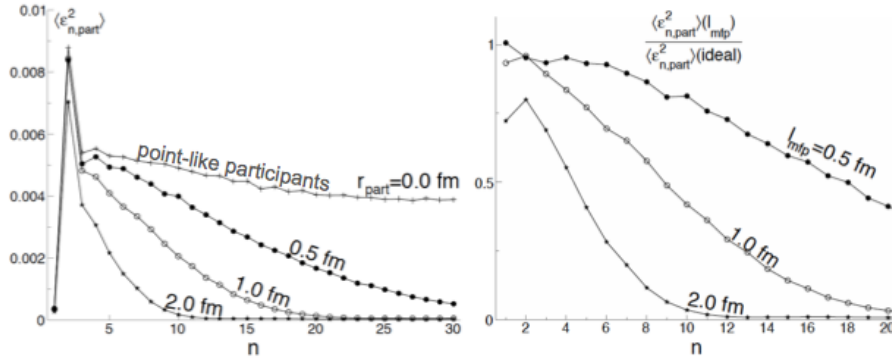


Figure 1: Left panel: $\langle \epsilon_{n,\text{part}}^2 \rangle$ for 0-5% central Au+Au collisions from a Glauber Monte Carlo where participants are either treated as point-like or they are smeared over a region of size r_{part} . We include the oblate shape of Au nuclei in our calculation. Right panel: the ratio of the curves on the left to the point-like curve.

In this calculation we introduced the length scale r_{part} causing the higher terms in $\langle \epsilon_{n,\text{part}}^2 \rangle$ to be washed out. That effect is more general though and we believe it is important for understanding correlations and v_n fluctuations. One can also consider what happens when particles free-stream for some amount of time τ_{fs} before they interact; that will also introduce a length scale $c\tau_{fs}$ which leads to a similar reduction of higher terms [12]. One can also consider the effect of a mean-free-path (l_{mfp}) on the ability of the fireball to convert higher $\langle \epsilon_{n,\text{part}}^2 \rangle$ terms into v_n^2 [14, 15]. If a particle on average travels for a distance l_{mfp} between interactions, it is clear that higher $\langle \epsilon_{n,\text{part}}^2 \rangle$ terms will not become manifest in v_n^2 . Fig. 2 shows a schematic illustration of this idea. If our probe has a l_{mfp} in the fireball, then we will be blind to features smaller than l_{mfp} . All these effects will act to wash out the higher harmonics so we expect v_n^2 to drop with n . Since v_n^2 is related to $dN/d\Delta\phi$ by a Fourier transform, and since a Fourier transform of a Gaussian

is a Gaussian, all we need to reproduce the near-side Gaussian ridge in two particle correlations, is for v_n^2 to drop with n with an approximately Gaussian shape. The right panel of Fig. 1 shows that this is a reasonable expectation from viscous effects.

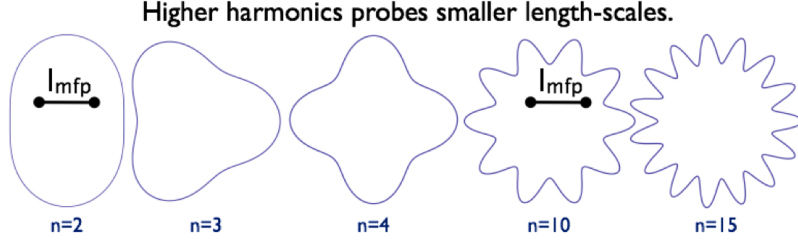


Figure 2: Schematic illustration of the interplay between a length scale like the mean-free-path and the higher harmonics.

The ridge amplitude A_1 is found by measuring $\Delta\rho/\sqrt{\rho_{ref}}$ (the pair density ρ minus the reference pair density ρ_{ref} scaled by $\sqrt{\rho_{ref}}$) vs $\Delta\phi$ and $\Delta\eta$ [16]. A fit function is devised to describe the correlation. The fit function has a $\Delta\phi$ independent term, a $\cos(\Delta\phi)$ and $\cos(2\Delta\phi)$ term, and a near-side 2-D Gaussian. The fit function describes the data well [16]. Here we work with the conjecture that the 2-D Gaussian is a manifestation of $\langle\epsilon_{n,part}^2\rangle$. Based on this conjecture, we can try to calculate the centrality dependence of A_1 . Our result for A_1 will be related to v_n^2 so we need to know the conversion efficiency c of $\langle\epsilon_{n,part}^2\rangle$ into v_n^2 . The conversion efficiency will depend on particle density. In Fig. 3 we show v_2/ϵ vs density $(1/S)dN/dy$ from the STAR Collaboration [17] with a fit function to parameterize the data. The figure shows $v_2\{4\}$ divided by the eccentricity calculated with respect to the reaction plane from a CGC model [18]. We will take this to estimate our conversion efficiency with the understanding that the different results obtained from CGC and Glauber models gives rise to at least a 30% uncertainty in the correct conversion efficiency.

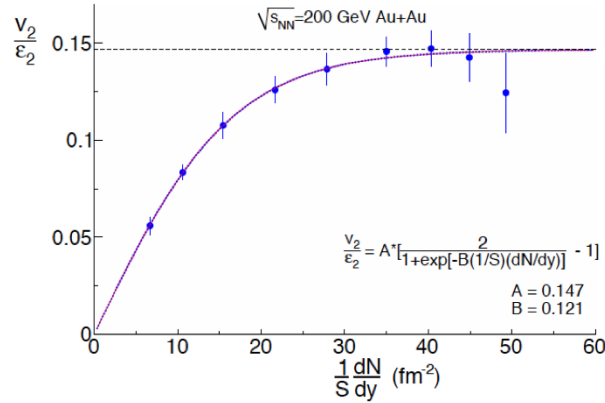


Figure 3: The ratio of $v_2\{4\}$ over ϵ_{std} from a CGC model vs $(1/S)dN/dy$.

Since a $\cos(\Delta\phi)$ and $\cos(2\Delta\phi)$ term have already been subtracted from $\Delta\rho/\sqrt{\rho_{ref}}$ in order to obtain A_1 , our estimate of A_1 can be made simpler if we predict the $n = 3$ component of the near-side ridge and scale that up to get the full amplitude. The $n = 3$ component is found from

$$\frac{1}{2\pi} \int_{-\pi}^{\pi} \frac{\Delta\rho}{\sqrt{\rho_{ref}}} \cos(3\Delta\phi) d\Delta\phi = 0.039 A_1. \quad (1)$$

The azimuthal width σ of the near-side Gaussian is weakly dependent on centrality so we use a typical value of $\sigma = 0.65$. The factor of 0.039 will be used to relate our prediction for $\langle\epsilon_{n,part}^2\rangle$ to the amplitude A_1 . Since $\Delta\rho/\sqrt{\rho_{ref}}$ is a per-particle measure instead of a per-pair measure, we need to include the particle density $\rho_0 = \frac{1}{4\pi} \frac{dN}{dy}$. Putting

$\langle \varepsilon_{3,part}^2 \rangle$ together with the conversion efficiency c , particle density ρ_0 , and the factor of 0.039 to map from the $n = 3$ component to a Gaussian amplitude, we find

$$A_1 \approx \rho_0 c \varepsilon_{3,part}^2 / 0.039. \quad (2)$$

We take ρ_0 from data, c from Fig. 3, and $\langle \varepsilon_{3,part}^2 \rangle$ from our Monte-Carlo Glauber model.

The Rise and Fall of the Ridge: The right panel of Fig. 4 shows our estimate of the ridge amplitude A_1 based on $\varepsilon_{n,part}^2$ vs centrality parameter $\nu = 2N_{bin}/N_{part}$. The left panel shows the preliminary STAR data. Our estimate for the amplitude is only approximate since we've applied the conversion efficiency for $n = 2$ to $n = 3$ and as discussed before, we expect the efficiency to drop with n . This will lead us to overestimate the contribution from $\langle \varepsilon_{n,part}^2 \rangle$ to the ridge. On the other hand, we used a CGC based eccentricity model to extract the conversion efficiency but a Glauber model for $\langle \varepsilon_{3,part}^2 \rangle$. This should cause us to under-estimate the ridge contribution; to some extent canceling the previous overestimate. We find that our estimate of A_1 agrees quite well with data. The centrality dependence is particularly interesting: our A_1 , like the data, starts at a small value and rises much faster than expectations from a Glauber Linear Superposition model (GLM) which assumes that correlations grow as N_{bin}/N_{part} . The rise continues until A_1 reaches a maximum near $\nu = 5$, then A_1 falls again. This rise and fall is also seen in the preliminary 62.4 GeV data [16] and has no natural explanation in any of the other proposed scenarios for the ridge formation. In our picture, the rise and fall is related simply to the geometry and it's fluctuations. $\langle \varepsilon_{3,part}^2 \rangle$ falls with N_{part} since the larger N_{part} leads to smaller fluctuations. But $N_{part} \langle \varepsilon_{3,part}^2 \rangle$ first rises then falls. This rise and fall is due the asymmetry of the overlap region which shows up even for $\langle \varepsilon_{3,part}^2 \rangle$. Since both c and ρ_0 are increasing with centrality, the product of $\rho_0 c \langle \varepsilon_{3,part}^2 \rangle$ rises until very central collisions and then falls as shown in the figure. The observation that the rise and fall shows up in the near-side ridge amplitude suggests that the near-side ridge is likely dominated by initial geometry fluctuations.

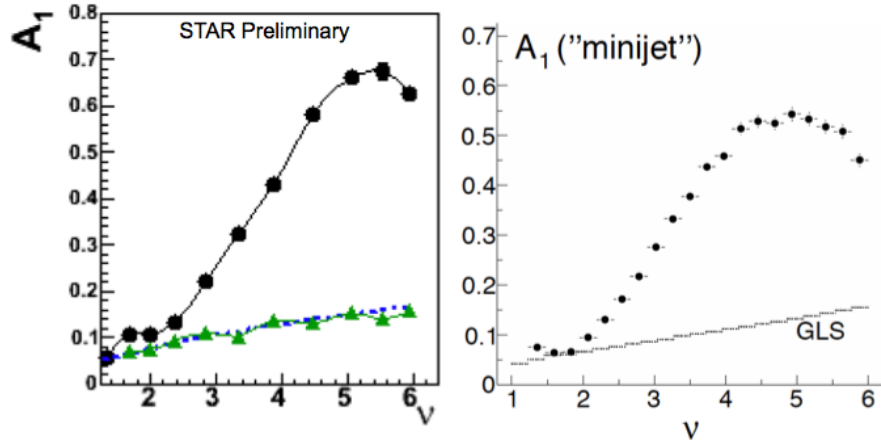


Figure 4: Left panel: measured near-side ridge amplitude A_1 vs centrality measure $\nu = 2N_{bin}/N_{part}$. Right panel: contribution to the ridge from initial state geometry fluctuations.

Transfer Functions: Our explanation for the centrality dependence of A_1 is based on the three simple premises listed earlier and provides a natural explanation for the rise and fall of the ridge. Initial estimates of the amplitude agree to within our uncertainties. This suggests that geometry fluctuations in the initial overlap region are converted into momentum space giving rise to the near-side ridge structure. We discussed that we expect the conversion efficiency to drop with n since effects like initial-state free-streaming and mean-free-path will wash out the higher harmonic terms. Measuring the conversion efficiency $c_n = \frac{v_n\{2\}^2}{\varepsilon_{n,part}\{2\}^2}$ as a function of n , centrality, and particle kinematics will provide information on those effects. It will be particularly interesting to measure c_n as a function of $\Delta\eta$ to understand how de-coherence affects manifest in the longitudinal direction.

In Fig. 5 we show the conversion efficiency $v_n\{2\}^2/\varepsilon_{n,part}^2$ for intermediate p_T di-hadron correlations from STAR [6].

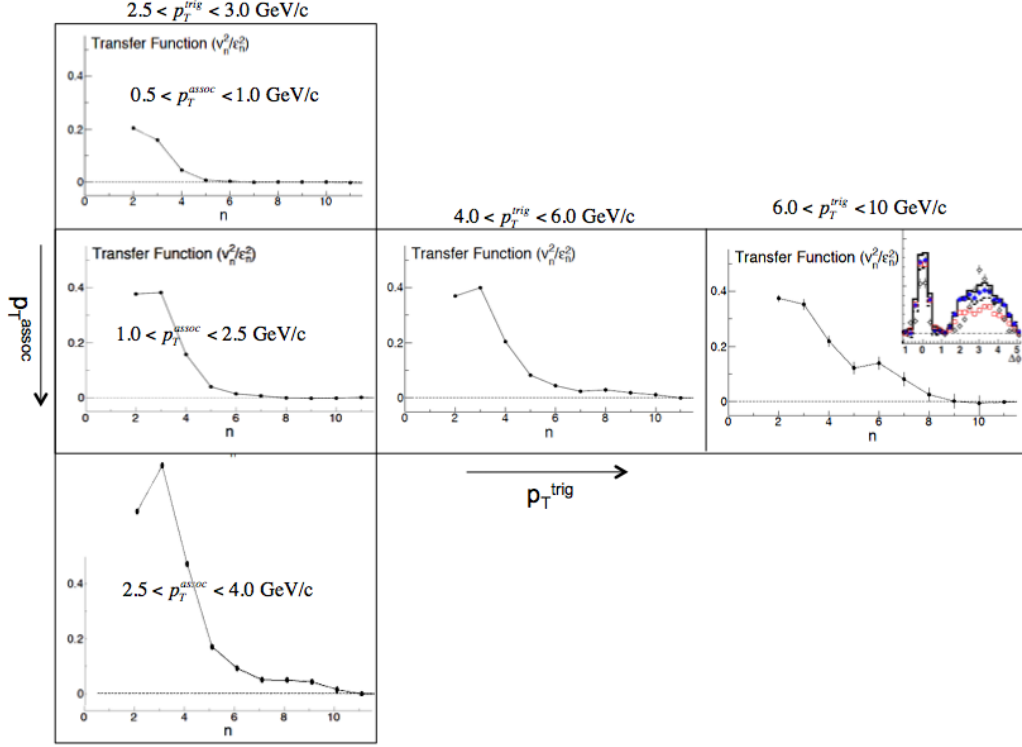


Figure 5: The transfer function $v_n\{2\}^2/\epsilon_{n,part}^2$ for intermediate p_T di-hadron correlations from 20-60% central 200 GeV Au+Au collisions [6].

The panels show various combinations of trigger particle and associated particle p_T selections. Intermediate p_T di-hadron data rather than showing an away-side Gaussian, show two peaks shifted to either side of $\Delta\phi = \pi$. It has been suggested that this is evidence of conical emission on the away-side of the higher p_T trigger particle [19, 20]. The previously ignored effects of v_3^2 which were, however, could explain some or all of these novel structures [9]. To investigate these structures, we look at the p_T dependence of $c_n(p_T^{trig}, p_T^{assoc})$. By plotting $v_n\{2\}^2/\epsilon_{n,part}^2$ from these correlations, we hope to see what portion of those correlations can be explained by geometric effects. For relatively lower momentum cuts, we find that $c_n(2.5 \text{ GeV}, 0.5 \text{ GeV})$ behaves much as we expect from mean-free path effects for example; the higher terms drop off monotonically similar to Fig. 1 (right). But for higher p_T^{assoc} cuts c_n shows a pronounced peak at $n = 3$. See $c_n(2.5 \text{ GeV}, 2.5 \text{ GeV})$ for example. This feature disappears again however when a large enough p_T^{trig} cut is applied. For $p_T^{trig} > 6 \text{ GeV}$ for example, we see only effects due to the presence of correlations from jets. It remains interesting to speculate about the possible source of that local maximum at $n = 3$ for intermediate p_T di-hadron correlations (whether it's due to a suppression of the lower harmonic super-horizon modes [21], mach-cones [20] or some other acoustic effects [22]). It seems to be larger than trivially expected from $\epsilon_{n,part}^2$. We note however that a complete investigation of the systematic errors on our Glauber Model has not been carried out. We include the oblate shape measured for the Au nucleus. That oblateness leads to a large enhancement of the $n = 2$ component of $\epsilon_{n,part}^2$. Reducing the oblateness of the Au nucleus could therefore reduce or eliminate the prominence of the $n = 3$ term in c_n . This remains for further investigation.

Conclusions: We presented the participant eccentricity vs harmonic when the participants are treated as point-like or smeared over a radius r_{part} . The larger values of r_{part} wash out the higher harmonic eccentricities. We argued that, similarly, a large mean-free-path should wash out higher harmonics of v_n . Such an effect could lead to a Gaussian peak in two particle correlations at $\Delta\phi = 0$. We've calculated the contribution to the near-side Gaussian peak that we expect from initial density fluctuations. We based our calculation on three premises 1) that the expansion of the fireball created in heavy-ion collisions converts anisotropies from coordinate-space into momentum-space, 2) the conversion

efficiency depends on particle density, and 3) the relevant expansion plane is the participant plane. Following these premises, we find that the near-side peak from density fluctuations should rise rapidly, reach a maximum just before the most central events, then fall. Our estimate of the magnitude is in agreement within our uncertainties with the available data and the shape matches that seen in the data. This is the only calculation to correctly describe the rise and fall of the ridge amplitude. We conclude therefore that density fluctuations are likely the dominant source for the low p_T ridge-like correlations. We have also shown the ratio of the final momentum space correlations $v_n\{2\}^2$ to the initial coordinate-space eccentricities $\varepsilon_{n,part}^2$ for intermediate p_T di-hadrons. We find that for intermediate p_T correlations the $n = 3$ term is larger than $n = 2$. This suggests that even after taking into account initial density fluctuations, some interesting signal may exist in the intermediate p_T di-hadron data.

References

- [1] W. Reisdorf and H. G. Ritter, Ann. Rev. Nucl. Part. Sci. **47**, 663 (1997); N. Herrmann, J. P. Wessels and T. Wienold, Ann. Rev. Nucl. Part. Sci. **49**, 581 (1999).
- [2] F. Karsch, PoS C **POD07** (2007) 026 [arXiv:0711.0656 [hep-lat]]; PoS **LAT2007** (2007) 015 [arXiv:0711.0661 [hep-lat]].
- [3] M. Daugherty [STAR Collaboration], arXiv:0806.2121 [nucl-ex].
- [4] J. Adams et al. [STAR Collaboration] Phys. Rev. Lett. **95**:152301, (2005); F. Wang [STAR Collaboration], J. Phys. G **30** (2004) S1299 [arXiv:nucl-ex/0404010]; J. Adams et al. [STAR Collaboration], Phys. Rev. C **73** (2006) 064907 [arXiv:nucl-ex/0411003]; J. Putschke, J. Phys. G **34** (2007) S679 [arXiv:nucl-ex/0701074]; J. Adams et al. [Star Collaboration], Phys. Rev. C **75** (2007) 034901 [arXiv:nucl-ex/0607003]; Brijesh Srivastava for the STAR Collaboration, Int. J. Mod. Phys. E16, 3371 (2008); Feb. 4th-10th, 2008, to be published in conference proceedings; A. Adare et al. [PHENIX Collaboration], Phys. Rev. C **78** (2008) 014901 [arXiv:0801.4545 [nucl-ex]]; B. Alver et al. [PHOBOS Collaboration], arXiv:0804.3038 [nucl-ex].
- [5] B. Alver, G. Roland, Phys. Rev. **C81**, 054905 (2010).
- [6] J. Adams et al. [STAR Collaboration], Phys. Rev. Lett. **97**, 162301 (2006) [arXiv:nucl-ex/0604018].
- [7] T. A. Trainor, Mod. Phys. Lett. A **23**, 569 (2008).
- [8] M. L. Miller, K. Reygers, S. J. Sanders and P. Steinberg, Ann. Rev. Nucl. Part. Sci. **57**, 205 (2007) [arXiv:nucl-ex/0701025].
- [9] P. Sorensen, J. Phys. G: Nucl. Part. Phys. **37** 094011 (2010).
- [10] A. Dumitru et al., Nucl. Phys. **A810**, 91 (2008); S. Gavin, L. McLerran, G. Moschelli, Phys. Rev. **C79**, 051902 (2009).
- [11] J. Takahashi et al., Phys. Rev. Lett. **103**, 242301 (2009).
- [12] H. Petersen et al., [arXiv:1008.0625 [nucl-th]].
- [13] D. Teaney and L. Yan, arXiv:1010.1876 [nucl-th].
- [14] A. Mocsy and P. Sorensen, arXiv:1008.3381 [hep-ph].
- [15] B. H. Alver, C. Gombeaud, M. Luzum and J. Y. Ollitrault, Phys. Rev. C **82**, 034913 (2010).
- [16] M. Daugherty, Ph. D. Thesis, <http://drupal.star.bnl.gov/STAR/theses/ph-d/>
- [17] K. H. Ackermann et al. [STAR Collaboration], Phys. Rev. Lett. **86**, 402 (2001); J. Adams et al. [STAR Collaboration], Phys. Rev. C **72**, 014904 (2005).
- [18] H. J. Drescher, A. Dumitru, A. Hayashigaki and Y. Nara, Phys. Rev. C **74**, 044905 (2006) [arXiv:nucl-th/0605012]; H. J. Drescher and Y. Nara, Phys. Rev. C **76**, 041903 (2007) [arXiv:0707.0249 [nucl-th]].
- [19] J. Adams et al. [STAR Collab.], Phys. Rev. Lett. **95**, 152301 (2005); M. McCumber and J. Frantz, Acta Phys. Hung. A **27**, 213 (2006).
- [20] J. Casalderrey-Solana, J. Phys. G **34**, S345 (2007); J. Casalderrey-Solana, E. V. Shuryak and D. Teaney, J. Phys. Conf. Ser. **27**, 22 (2005) [Nucl. Phys. A **774**, 577 (2006)]; H. Stocker, B. Betz and P. Rau, PoS C **POD2006**, 029 (2006).
- [21] A. P. Mishra, R. K. Mohapatra, P. S. Saumia and A. M. Srivastava, Phys. Rev. C **77**, 064902 (2008).
- [22] R. Andrade, F. Grassi, Y. Hama and W. L. Qian, J. Phys. G **37**, 094043 (2010).